Journal of Nepal Geological Society, 2019, vol. 59, pp. 9–18
https://doi.org/103126/jngs.v59i0.24982

Assessment of liquefaction susceptibility in Quaternary deposits: A case study from Jhapa Bazar area, eastern Nepal

Pradeep Paudyal
Amrit Science Campus, Tribhuvan University, Kathmandu, Nepal

Email: ppaudyal.geo@gmail.com

ABSTRACT

Liquefaction is generally experienced in unconsolidated fine- grained sediments during the large earthquakes. In Nepal, the southern part of the country comprises Quaternary deposits called as Indo-Gangetic deposit. Sand and silts are dominant in this zone, where groundwater level is also relatively high. In eastern Nepal, several places have experienced ground fissures, sand boiling, and liquefaction during the large earthquakes in the past history. There are several factors including soil properties, groundwater level, grain size of sediments and ground acceleration that contribute to ground liquefaction. The eastern Nepal faced a devastating earthquake in 1934 (magnitude of 8.4), Udaypur earthquake in 1988 (magnitude of 6.6) and Sikkim-Nepal earthquake in 2011 (magnitude of 6.8) and there is still possibility of similar large earthquakes in future. Liquefaction was reported in many places during Nepal-Bihar earthquake that indicates possibility of liquefaction during similar earthquakes. Liquefaction potential values are calculated from sediment grain size, subsurface geology, groundwater level and standard penetration test (SPT)-N values. The epicenter, magnitude, and other parameters of Nepal-Bihar earthquake have been used to calculate the liquefaction potential. A liquefaction susceptibility map has been prepared in the study area that comprises low, medium, and high liquefaction potential zones. About 20% of the study area including Jhapa Bazar and its surrounding area seems highly susceptible to liquefaction.

Keywords: Liquefaction Potential, Susceptibility, Fine-grained sediments, eastern Nepal

Paper Received: 27 Mar 2019 **Paper Accepted:** 5 May 2019

INTRODUCTION

Liquefaction is always associated with an earthquake. It is experienced if the earthquake occurred in non-consolidated sediments dominant with sand and silt. The term 'liquefaction' was originally used by Mogami and Kubo in 1953 (Kramer, 1996). It is a process in which the soil suddenly undergoes change from solid state to show liquid behavior. The generation of excess pore pressure under undrained loading condition is principal criteria for all liquefaction. It is more likely to occur in loose and moderately saturated granular soil with drainage as in silty sand or sand and gravel covered with impermeable sediments (Youd and Idriss, 2001). During an earthquake event, the ground shaking increases pore water pressure in consolidated deposits, which reduces the effective stress, and therefore reduces the shear strength of soil. If the saturated silt, sand or gravel is capped with dry soil or thin impermeable layer, the excess water sometimes comes to the surface making cracks in the capped layers. At this time, the underneath sand comes out with a high pressure and thrown to air as water fountain, which is termed as sand boiling.

As an earthquake, the liquefaction is also a major contributor to urban seismic risk. The deposits most susceptible to liquefaction are well-sorted (having similar grain size), cohesionless sands and silts that are not consolidated properly due to less geological age of formation. Such deposits are often found along riverbeds, beaches, floodplains, dunes, and areas where windblown silt (loess) and sand have accumulated. In Nepal, the Tarai region is made up of river worked sediments that was deposited within the last 10,000 years (Holocene age). In the middle and southern part of the Tarai Plain, sand and silt are dominant soil type. The groundwater level can also be reached in short depth. The present study area lies in the Tarai Plain that comprises unconsolidated sand, silt, and gravels as main soil type. Therefore, the liquefaction hazard assessment is very crucial for the study area.

STUDY AREA AND GEOLOGY

The study area lies in southern part of the Jhapa District, eastern Nepal that covers Jhapa Bazar and nearby areas. It comprises the area of the Shivagunj, Panchgachhi, Sharanamati, Kumarkhod, and Tagadubba VDCs (Fig. 1). Physiographically, the study area lies in the Tarai Plain, which has very gentle slope facing towards south with less than average slope of 5 degree. The study area covers about 148.88 sq. km., where elevation ranges from 71 m. to 116 m. Being a part of Tarai Plain, climatic condition of the study area is sub-tropical that experiences four seasons: pre-monsoon, monsoon, post-monsoon, and winter. The temperature ranges from 15 ^{0}C to 33 ^{0}C in the study area.

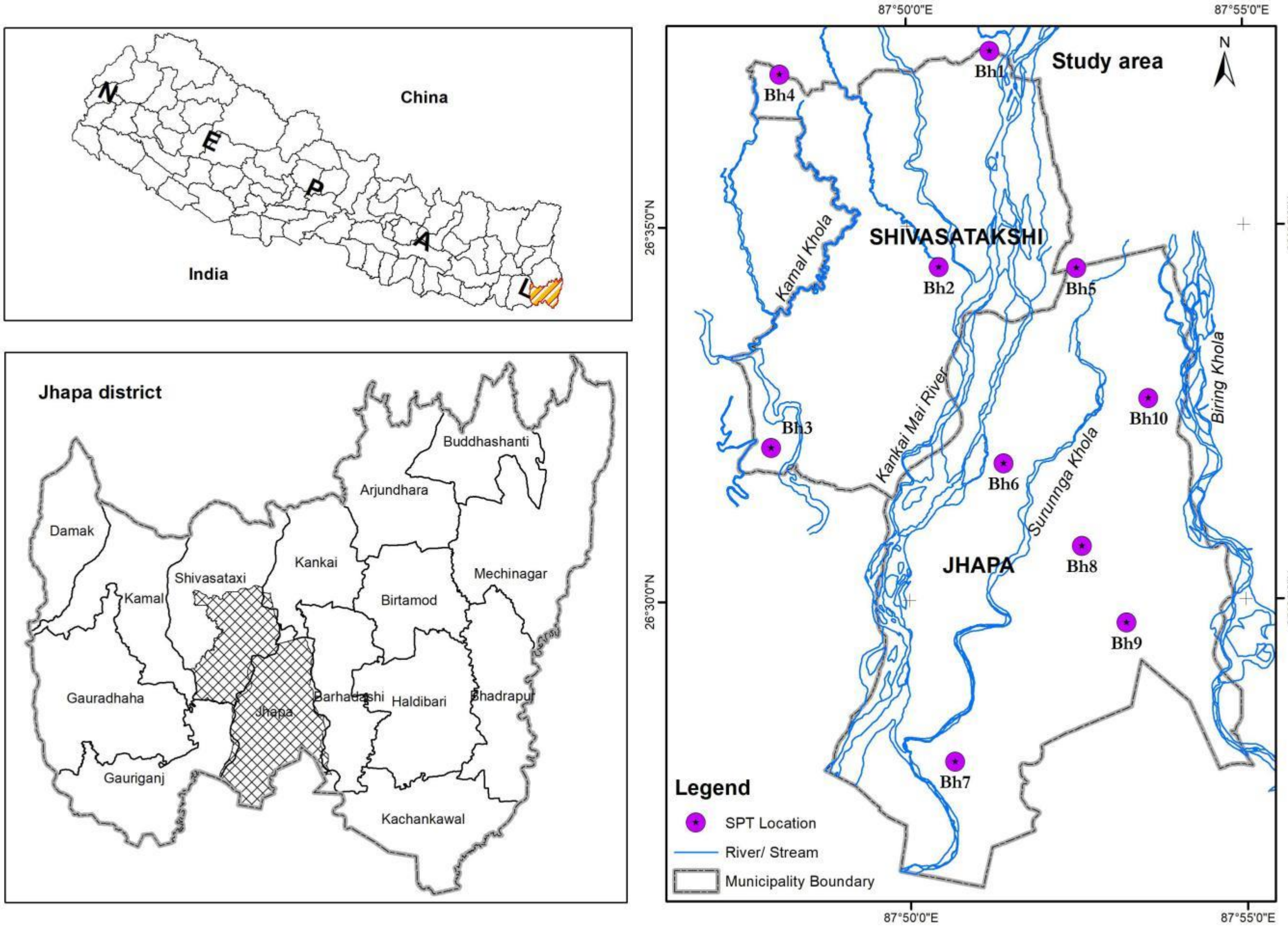

Fig. 1: Location map of study area

Since the study area lies in the Tarai Plain, northern extension of the Indo-Gangetic Plain, the geology comprises only the Quaternary deposits of fluvial sediments. These alluviums are very loose and derived from Himalayan range as severe erosion during the upliftment of the Himalaya since Miocene time to present day. The geological map of the study area presents the spatial distribution of these sedimentary deposits based on the grain size, texture, and geomorphic features they made (Fig. 2; Table 1).

METHODOLOGY

Borehole logging and SPT-test

Sub-surface geological setting is studied through borehole logs. There were 10 wash borings sunk in the study area to penetrate 10 m. depth at each borehole site (Fig. 1). The information obtained from these lithologs was used to study the underground geology and hydrogeological setting. The lithologs of these boreholes were correlated with each other to study the distribution of palaeo-channelization of streams. Standard penetration tests (SPT) were also done at all these boreholes in 1.5 m depth interval (Fig. 3). The SPT-N values were calculated and used in liquefaction susceptibility analysis.

Liquefaction susceptibility

Liquefaction potential is a function of both the susceptibility of surficial deposits to liquefaction and the probability that earthquake ground motions will exceed a specified threshold level, or opportunity (Witter et al., 2006). Soil liquefaction is one the destructive geotechnical hazard associated with earthquakes that may cause failure of physical infrastructures resulting a huge loss of lives and property (Pokhrel et al., 2013). A liquefaction susceptibility map presents the distribution of liquefaction potential experienced by surficial deposits with different physical properties and variations in hydrologic conditions. The opportunity for liquefaction is also determined by the proximity of seismic sources, and the magnitude and recurrence interval of earthquakes. The seismic sources are capable of generating ground shaking and local site conditions control the amplification or attenuation of shaking. The liquefaction potentiality basically depends on the engineering and geo-technical properties of soil, water table, and strength of ground motion during an earthquake. The liquefaction

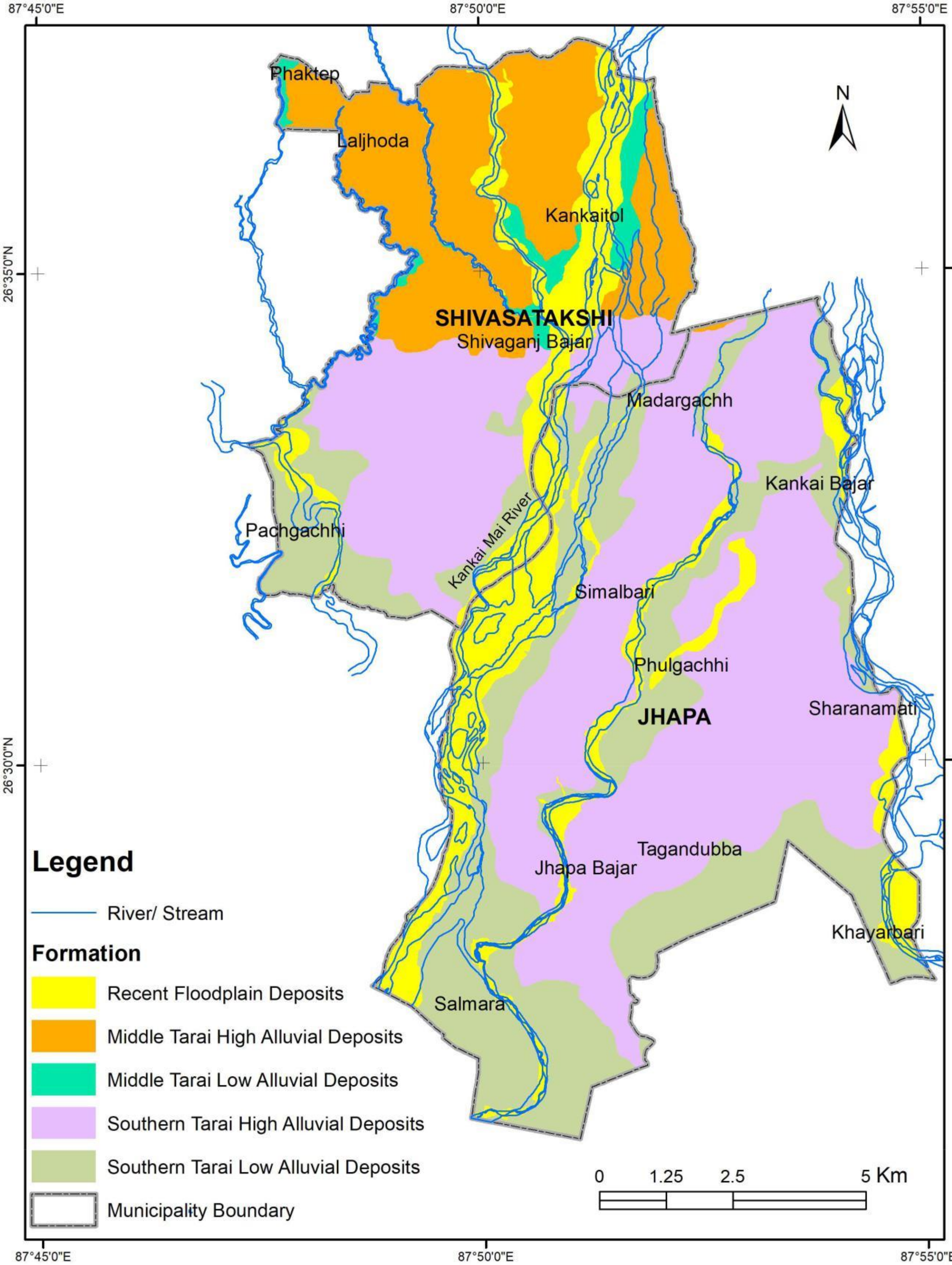

Fig. 2: Geological map of study area

Table 1: Geological subdivisions of study area

Zone	Group	Formation	Main characteristics
Indo-Gangetic Plain (Tarai Plain)	Active River Bed Deposits	Recent Floodplain Deposits	Dominance of gravel to sand sized sediments; frequent flooding zone; river beds and active floodplains
	Middle Tarai	Middle Tarai High Alluvial Deposits	Dominance of sand and silts; very old alluvial plains; Well-to moderate- drained soil; favorable to get groundwater
		Middle Tarai Low Alluvial Deposits	Low-lying ancient alluvial flood plains on the banks of current river course; dominance of silt and clay on upper parts and sand on lower
	Southern Tarai	Southern Tarai High Alluvial Deposits	Ancient alluvial plains found in southern region; dominance of clay and silt with less sand; water logging in heavy rainfall
		Southern Tarai Low Alluvial Deposits	Low-lying alluvial plain on the banks of present river courses; dominance of clay and silt with less sand; water logging in monsoon

susceptibility, thus can be defined as a function of the geotechnical properties of soil and topographic position of the unit. There are several factors that affect the liquefaction susceptibility, such as sedimentation process, age of sedimentary deposits, depth of groundwater table, engineering and geotechnical properties of soil/sediment grains, depth of burial, soil density and packing, proximity to a free face and ground slope (Youd and Perkins, 1978). Liquefaction hazard zonation shows the spatial distribution of liquefaction potential zones in a study area. Several studies have been carried out in liquefaction susceptibility zonation (Pokhrel et al., 2010). Liquefaction susceptibility zones can be determined by two approaches: qualitative and quantitative. Liquefaction potentiality has been calculated employing quantitative approach, where the following processes and parameters were considered:

- Sediment grain size, their packing, and type of origin (natural or filled-up),
- Elevation of groundwater table,
- Age of sedimentary deposits and depositional environment,
- Historical events of liquefaction in the area,
- Surface and sub-surface geological units and thickness of individual layers or horizons,
- Spatial distribution of SPT-N values measured in the study area, and
- The estimated 'ground motion threshold' required to initiate liquefaction.

Liquefaction susceptibility analysis

There are some studies on liquefaction susceptibility

Fig. 3: Manual wash boring for (a) SPT-test and (b) logs collected in SPT-tube

analysis that are based on qualitative approaches. Iwasaki et al. (1982) and Youd and Perkins (1978) are widely referred studies on analysis of liquefaction susceptibility following qualitative methods. In addition, there are several researches being carried out on liquefaction susceptibility following quantitative approaches such as Seed (1979), Seed and Idriss (1971), Iwasaki et al. (1984), and many others. In the present study, a quantitative approach presented by Iwasaki et al. (1984) has been used to analyze the liquefaction susceptibility. In this method, the liquefaction potentiality is estimated simply by using the fundamental properties of soils, viz. SPT-N value, unit weight of soil, mean particle diameter (D50), and maximum accelerated at the ground surface or peak ground acceleration (PGA).

The SPT-N values are obtained from the field based SPT tests carried out during the study. The mean particle diameter (D_{50}) was calculated by sieving the soil sample collected in SPT tube. The spatial distribution of shear wave velocity is taken from the website of USGS, which is used to calculate PGA using equation of Boore et al. (1997). The information on groundwater table is obtained from the borehole logs and nearby wells in the study area.

The liquefaction potential for an individual soil layer stands by comparing the resistance against liquefaction of this layer (R) with the driving dynamic force that could cause liquefaction (L). With these values, factor of safety with respect to liquefaction (F_L) is determined using the relation at an arbitrary depth (Iwasaki et al., 1984).

$$F_L = R/L \qquad \text{.......................(1)}$$

where, F_L for specific soil at certain location is less than 1.0, it can be said that the soil liquefies during an earthquake. In equation (1), L is the earthquake-induced dynamic load in soil element, which can be simply estimated by using the relation (Iwasaki et al., 1984) as:

$$L = \tau_{max} / \sigma'_v = (\alpha_{s\,max} \cdot \sigma_v \cdot r_d)/(g \cdot \sigma'_v) \text{....(2)}$$

where, τ_{max} is the maximum shear stress (in kgf/cm), α_s max is the PGA at ground surface (in gals), g is the acceleration of the gravity (=980 gals), σ_v is the total overburden pressure (in kgf/cm^2), σ'_v is effective stress (in kgf/cm^2) and r_d is the reduction factor expressed as:

$$r_d = 1 - 0.015z \text{ ....(3)}$$

where, z is depth in meters from the ground surface.

Similarly, *in-situ* resistance of the soil element to dynamic load in terms of R is calculated as:

$$R = 0.882\,(N/(\sigma'_v+0.7))^{0.5} + 0.225 \log_{10}(0.35/D_{50}) \text{ ....(4)}$$

for 0.04 mm = D_{50} = 0.6 mm, and

$$R = 0.882\,((N/(\sigma'_v+0.7))^{0.5}) - 0.05 \text{.............(5)}$$

for 0.6 mm = D_{50} = 1 mm

where, N is the number of blows, σ'_v is effective stress (in kgf/cm^2) and D_{50} is mean particle diameter (in mm).

The liquefaction potential in terms of potential index (PL) is defined as (Iwasaki et al, 1984):

$$P_L = \int_0^{20} F(z)W(z)dz \text{ ....(6)}$$

where, z is the depth in meters,

W(z) is depth-weighting factor, W(z)=10 – 0.5z,

F(z) = 1 – F_L(z) for F_L(z)= and F(z)=0 for F_L(z)>1.

The equation 6 considers just the soil profile in the top 20 m depth. The liquefaction potential (P_L) values range from 0 to 100 indicating no liquefaction to severe in condition. In this study, the soil layers above water table were considered as non-liquefiable layers. The cumulative liquefaction potential for a location at the surface (P_L) is classified according to following Table 2.

RESULT AND DISCUSSION

Sediment distribution and SPT-N values

There is not a great variance in sediment size and compactness in the study area. The thickness of topsoil varies from 10 cm to 50 cm, which is followed by layers of clay and fine- grained sand. In general, the grain size of sand gradually increases as increase in depth, however, there is thick clay layer (100 to 150 cm.) at a depth of about 5 m. in the Shivaganj Area (BH-1 and BH-2) that lies on the right bank of the Kankai River (Figs. 1 and 4). In southern parts as well as near to the Kankai River, pebble bearing sand layers are observed at different depths. The gravel and pebble bearing sand layers are observed below depth of 2.5 m in southern parts (BH-6, BH-7, and BH-8) and continues to depth of 10 m. It indicates that the Kankai River used to flow through east of present channel and laterally shifted towards west to come at present condition.

The upper sedimentary layers are composed with silt, clay, and sand, which are loosely packed. The SPT-N values are also very low in these layers. The lower sedimentary layers are composed of sand with pebbles and gravels. These layers are moderate to high dense. The SPT-N values in these layers are more than 10.

Spatial distribution of liquefaction potential

The liquefaction susceptible zones were identified based on the liquefaction potential index that were calculated by following the principle and methodology presented in Iwasaki

Table 2: Classification of Liquefaction Susceptibility

Value	Susceptibility class	Remarks
$P_L = 0$	No / Very Low Liquefaction	Liquefaction susceptibility is very low or not at all. Detailed investigation on soil liquefaction are not needed in general
$0< P_L <5$	Low	Liquefaction susceptibility is low. Detailed investigations on soil liquefaction are necessary for important structures
$5<P_L<15$	Moderate	Liquefaction susceptibility is moderately high. Detailed investigations for soil liquefaction are usually necessary
$15<P_L<25$	High	Liquefaction susceptibility is high. Detailed soil investigations are mandatory
$P_L >25$	Very High	Liquefaction susceptibility is very high. Area should be avoided for developing structures

et al. (1984). The liquefaction potential index is calculated from a number of complex equations that need various data such as average grain size at different vertical layers of soil, bulk density of the soil, SPT-N values at different layers of soil, depth to the groundwater table, etc. The calculated "Liquefaction Potential Index" (PL) varies from 0 to 100, which is later classified into very low, low, medium, high, and very high risk level.

In the present study, the peak ground acceleration (PGA) value in this area was obtained by using a seismic model proposed by Boore et al. (1997). For that, seismic source and magnitude of Nepal-Bihar Earthquake of 1934 (Magnitude 8.4) was considered. This calculation was based on assumption of reoccurrence of large earthquake similar to Nepal-Bihar earthquake of 1934 of magnitude 8.4 at the similar distance of 130 km to the epicenter. The distribution of PGA in the study area ranges from 119 gal to 123 gal that means there is moderate risk of seismic amplification when a large earthquake of magnitude 8.3 occurred at a distance of 130 km. For the calculation of liquefaction potential in this study, the modeled PGA values were used. The liquefaction potential index was calculated at 10 different sites (borehole sites) based on the methodology discussed above. Sequential Gaussian Simulation (SGSIM) model was applied to simulate the predicted results.

The liquefaction susceptibility has been categorized into three classes: Low, Medium, and High (Fig. 5). About 20.18% of the study area is highly susceptible to liquefaction. Similarly, about 22.03% and 28.61% of the study area are moderately high and moderately low susceptible to liquefaction, respectively. About 29.18% of the study area falls under low susceptible zone. In the northwestern part of the study area, there is low risk of liquefaction. The recent and old floodplain areas made by the Kankai River and the Satashi Khola might be under high risk of liquefaction (Fig. 5). In the south-western part of the study area, the liquefaction potential index ranges between 5 to 12, which indicates that the area around Panchgachhi and south lie under moderately low susceptible zone due to liquefaction. Besides, the recent floodplains of the Kankai River and the Baniyani Khola might be under high risk because of loose silts and high groundwater level. The liquefaction potential index ranges from 5 to 12 in the south-eastern part of the study area too. It shows the Khayarghari, south of Sharanamati, and Tagandubba area are moderately low susceptible. The Jhapa Bazar, Simalbari and adjacent areas are moderately high susceptible to liquefaction. The value of liquefaction potential index ranges from 12 to 15 in this area. The Kankai Bazar-Phulgachhi area and southernmost Salmara area are under high susceptible due to liquefaction. The value of liquefaction potential index is more than 15 in those areas. Detail soil investigation on liquefaction should be mandatory for all the large structures in these areas.

CONCLUSION

Liquefaction susceptibility assessment of an area is conducted by calculating spatial distribution of liquefaction potential index. The study area including Jhapa Bazar comprises unconsolidated sand, silt, and clay with subordinate gravels belonging to Quaternary deposits. The liquefaction susceptibility of the area seems to be affected by soil type, shallow groundwater table, and rivers that dissect the study area. There are five different types of geological units, which are mapped on the basis of soil characteristics and geomorphic features they have. A liquefaction susceptibility zonation map has been prepared to show the spatial distribution of liquefaction potentiality in the study area. The study shows that about 20% of the study area is highly susceptible to liquefaction after occurring a large earthquake similar to Nepal-Bihar earthquake of 1934.

ACKNOWLEDGEMENT

This study was done as a supplement to multi-hazard assessment in five the then VDCcs Shivaganj, Sharanawatai, Panchgachhi, Tagandubba, and Kumarkhod of the Jhapa District.

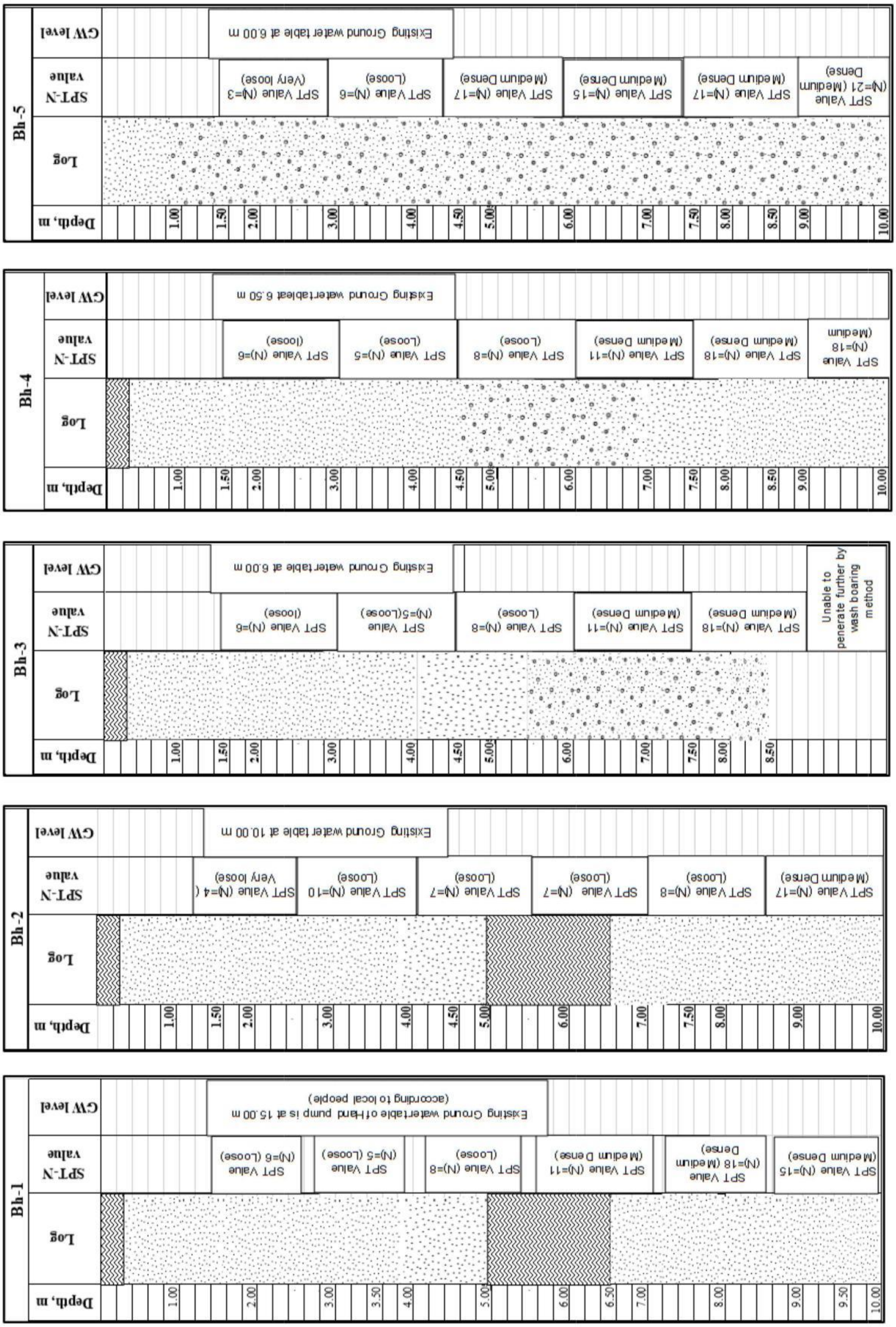

Fig. 4: Borehole logs showing different soil layers and respective SPT-N values (Contd...)

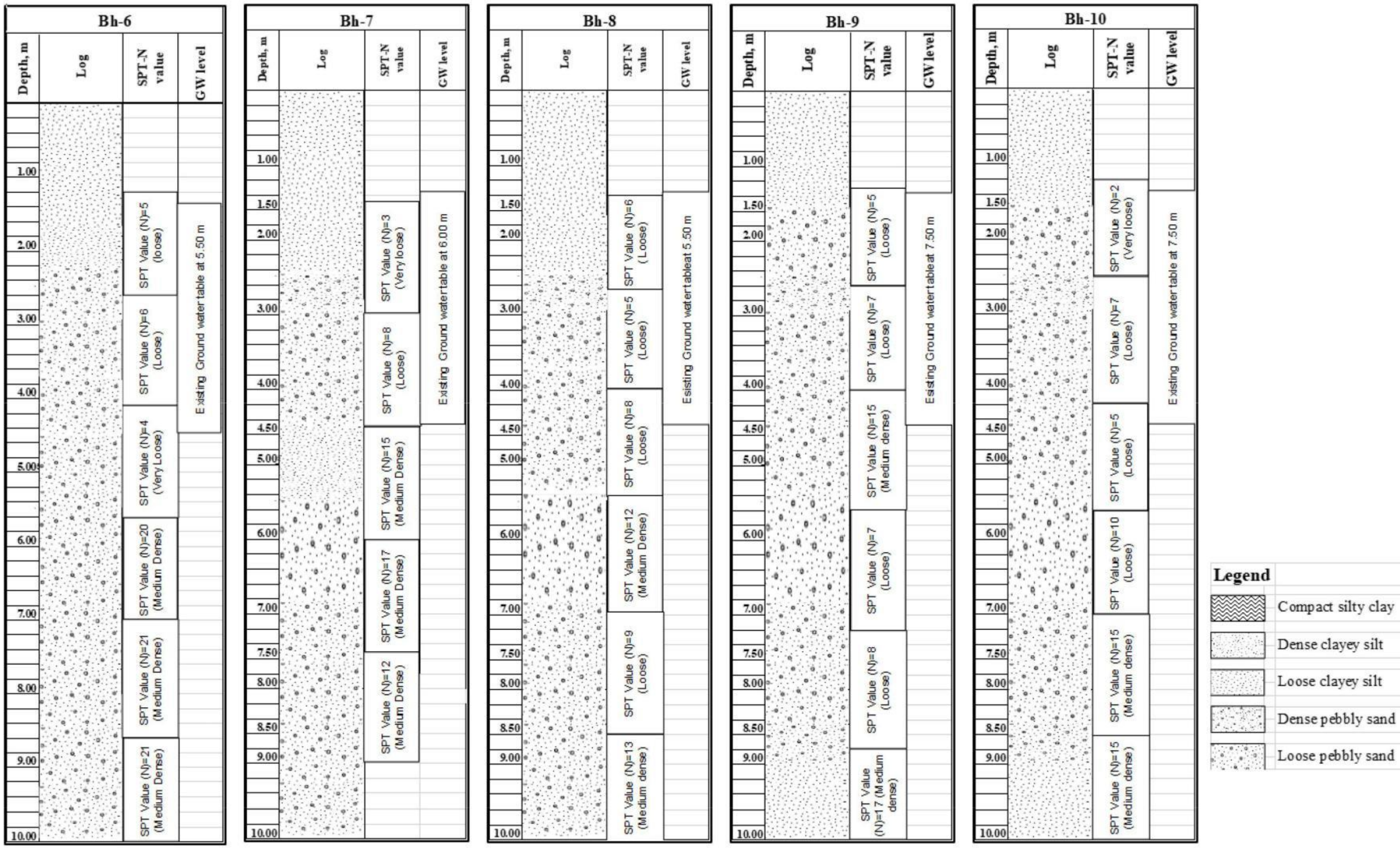

Fig. 4: Borehole logs showing different soil layers and respective SPT-N values (Contd...)

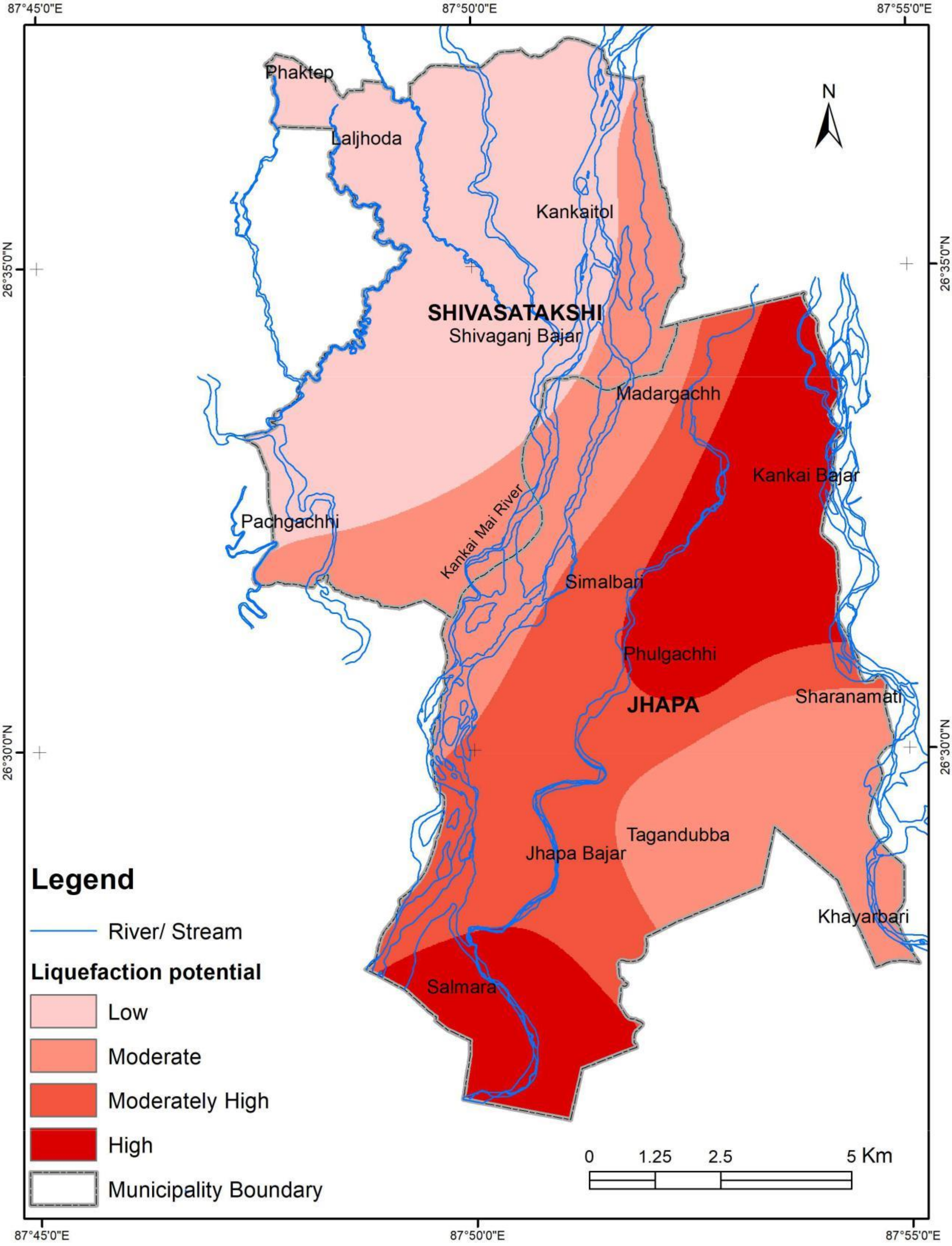

Fig. 5: Liquefaction susceptibility zoning of the study area

Author is grateful to Genesis Consultancy for supporting the entire project. In addition, author thanks Mr. Dilendra Pathak and Mr. Sobhit Thapaliya for their kind cooperation and support in geotechnical study. Author also thanks to two anonymous reviewers for peer reviewing and suggestions to improve this article.

REFERENCES

Boore, D. M., Joyner, W. B., and Fumai, T. E., 1997, Equations for Estimating Horizontal Response Spectra and Peak Acceleration from Western North American Earthquakes: A Summary of Recent Work. Seismological Research Letters, v. 68(1).

Iwasaki, T., Tokida, K., and Arakawa, T., 1984, Simplified procedures for assessing soil liquefaction during earthquakes. Soil dynamics and earthquake engineering, v. 3(1), pp. 49–58.

Iwasaki, T., Tokida, K., Tatsuoka, F., Watanabe, S., Yasuda, S., and Sato, H., 1982, Microzonation for soil liquefaction potential using simplified methods. 3rd Intl. Microzonation Conf. Proceeding.

Kramer, S. L., 1996, Geotechnical Earthquake Engineering (First ed.): Prentice Hall, 653p.

Pokhrel, R. M., Kuwano, J., and Tachibana, S., 2010, Liquefaction hazard zonation mapping of the Saitama City, Japan. Journal of Nepal Geological Society, v. 40, pp. 69–76.

Pokhrel, R. M., Kuwano, J., and Tachibana, S., 2013, A kriging method of interpolation used to map liquefaction potential over alluvial ground. Engineering Geology, v. 152 (1), pp. 26–37.

Seed, H. B. and Idriss, I. M., 1971, Simplified procedure for evaluating soil liquefaction potential. Jour. Soil Mechanics and Foundation Division, ASCE, v. 107, pp. 1249–1274.

Seed, H. B., 1979, Soil liquefaction and cyclic mobility evaluation for level ground during Earthquakes. Jour. Geotech. Engg. Div., ASCE, v. 105, pp. 201–255.

Witter, R. C., Knudsen, K. L., Sowers, J. M., Wentworth, C. M., Koehler, R. D., Randolph, C. E., Brooks, S. K., Gans, and K. D., 2006, Maps of Quaternary Deposits and Liquefaction Susceptibility in the Central San Francisco Bay Region, California. U. S. Geological Survey, 12p.

Youd, T. L. and Idriss, I. M., 2001, Liquefaction resistance of soils: Summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils. J Geotech. Geoenviron. Eng., 127(10), pp . 817–833, doi: 10.1061/ (ASCE) 1090-0241(2001)127:10(817).

Youd, T. L. and Perkins, D. M., 1978, Mapping liquefaction-induced ground failure potential. Proc. ASCE Civil Engg., v. 3, pp. 231–238.